T2K and HK
future near detectors

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NuFact15 @ Rio

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Introduction (1)

- T2K's approved POT by J-PARC PAC is 7.8e21.
  - Current delivered POT is 1.1e21 (15%).
- T2K started a discussion to extend the T2K running up to 25e21 POT*.
  - T2K also started a discussion about the collaboration efforts equivalent to 1.5~2 times statistical increase. (Horn current optimization, new SK samples/fiducial volume, …)

A case study on expected POT projection

Year (20XX)	15	16	17	18	19	20	21	22	23	24	25	26	27	28
POT (e21)	1.4	2.3	3.1	3.9	5.4	7.1	9.0	11.1	13.3	15.7	18.1	20.6	23.1	25.5
Power (MW)	0.36	0.40	0.46	0.70	0.80	0.89	1.06	1.12	1.19	1.29	1.29	1.33	1.33	1.33

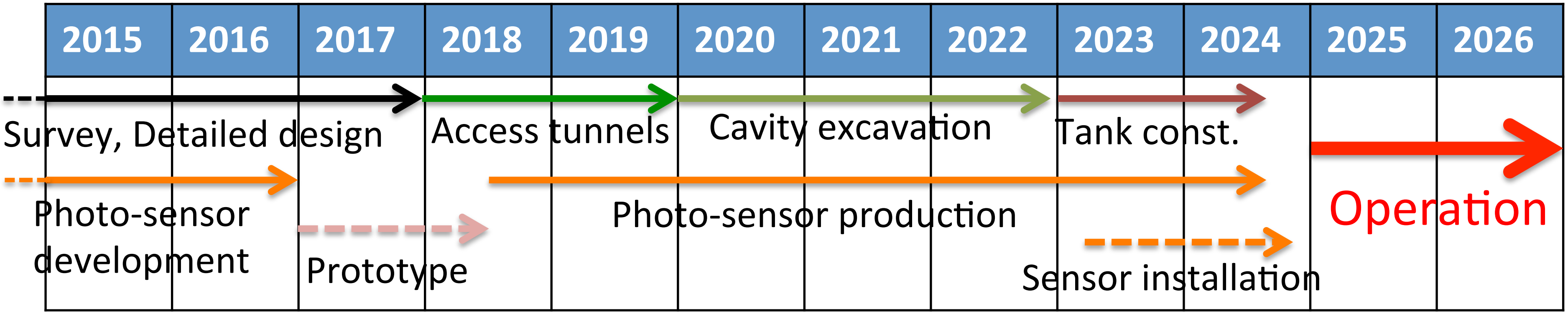
T2K

T2K extension

*** Workshop for Neutrino Programs with facilities in Japan**
http://www-conf.kek.jp/ws_nu_prog_in_jp/

Introduction (2)

- Hyper-K is a next generation underground water Cherenkov detector , the successor to Super-K.
  - The fiducial volume is 25 times larger than one of Super-K.
- Physics potential of Hyper-K + J-PARC ν beam*
  - CP phase precision: <19°
  - CP discovery coverage: 76% (3σ), 58% (5σ)
- Proposed timeline of Hyper-K



2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026

Survey, Detailed design

Access tunnels

Cavity excavation

Tank const.

Operation

Photo-sensor development

Prototype

Photo-sensor production

Sensor installation

* PTEP 053C02 (2015)

Condition: 1.5×10^{22} POT (7.5MW x 10^{7} sec.), $\sin^2 2\theta_{13}=0.1$, mass hierarchy known

Current T2K systematic errors

2014 → 2015

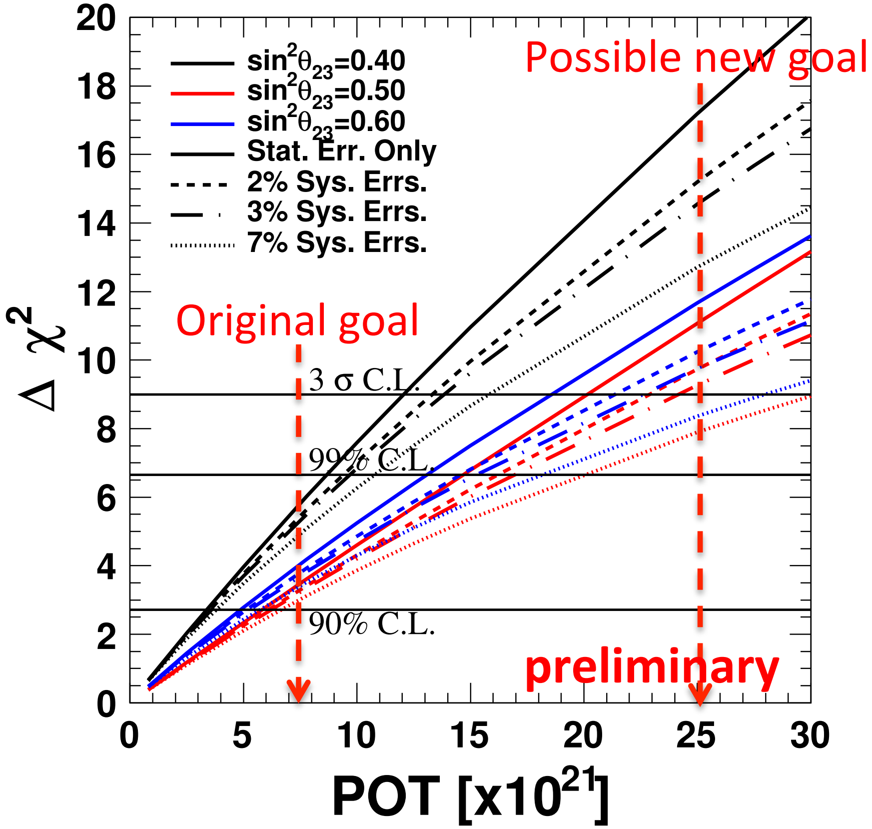
		ν_μ sample	ν_e sample	$\bar{\nu}_\mu$ sample	$\bar{\nu}_e$ sample
ν flux		16%	11%	7.1%	8%
ν flux and cross section	w/o ND measurement	21.8%	26.0%	9.2%	9.4%
	w/ ND measurement	2.7%	3.1%	3.4%	3.0%
ν cross section due to difference of nuclear target btw. near and far		5.0% *	4.7% *	10%	9.8%
Final or Secondary Hadronic Interaction		3.0%	2.4%	2.1%	2.2%
Super-K detector		4.0%	2.7%	3.8%	3.0%
total	w/o ND measurement	23.5%	26.8%	14.4%	13.5%
	w/ ND measurement	7.7%	6.8%	11.6%	11.0%

There are on-going efforts to reduce this nucleus-dependent errors with water target measurements in T2K near detectors.

* 2014 errors don't include the effect of multi-nucleon bound state at the neutrino interaction.

Effect of syst. errors for δ_{CP} measure. (1)

$\Delta\chi^2$ for resolving $\sin\delta_{CP} \neq 0$ in T2K



true $\delta_{CP} = -\pi/2$, true MH = NH
50% ν + 50% anti-ν mode

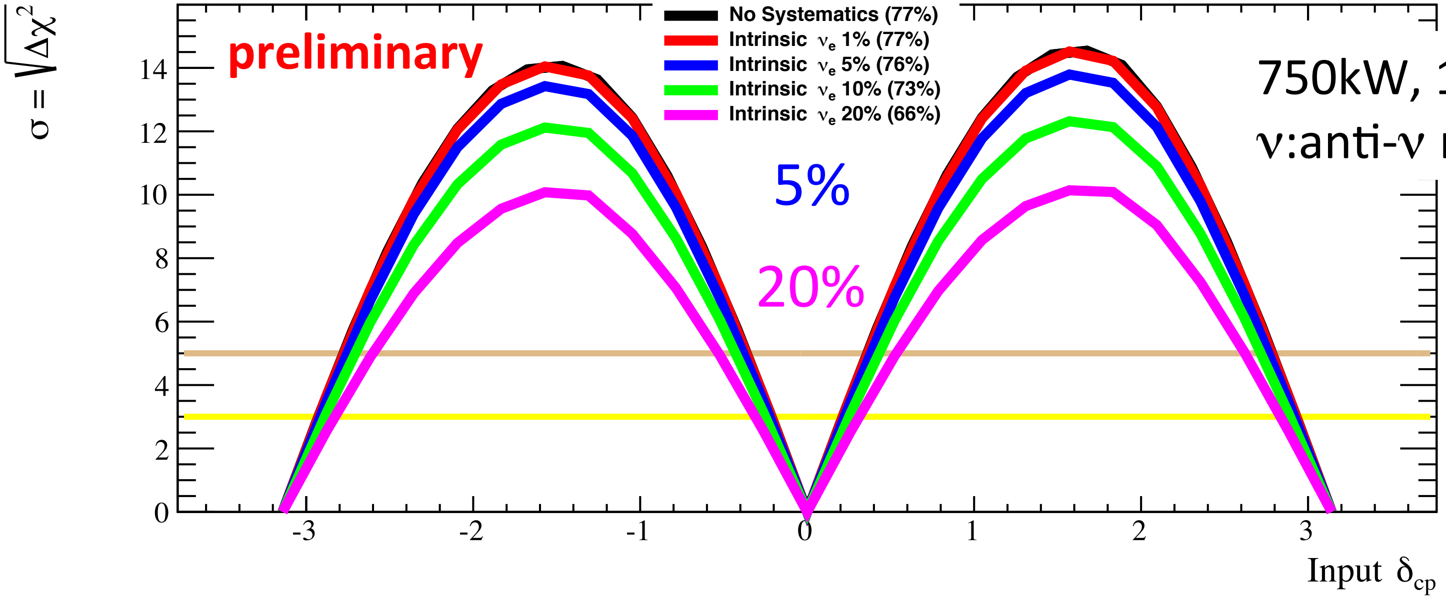
- At the goal of the T2K extension* (25e21 POT), reducing systematic errors from 7% to 2% is equivalent to 25% more data.
- Syst. errors should be reduced as much as possible to maximize the physics sensitivity.

* Discussion about the extension is just started. Nothing has been decided yet.

Effect of syst. errors for δ_{CP} measure. (2)

- Significance of CP violation vs. δ_{CP} w/ Hyper-K + J-PARC
  - Dominant syst. error is the intrinsic ν_e BG

Intrinsic ν_e uncertainty



750kW, 10 years

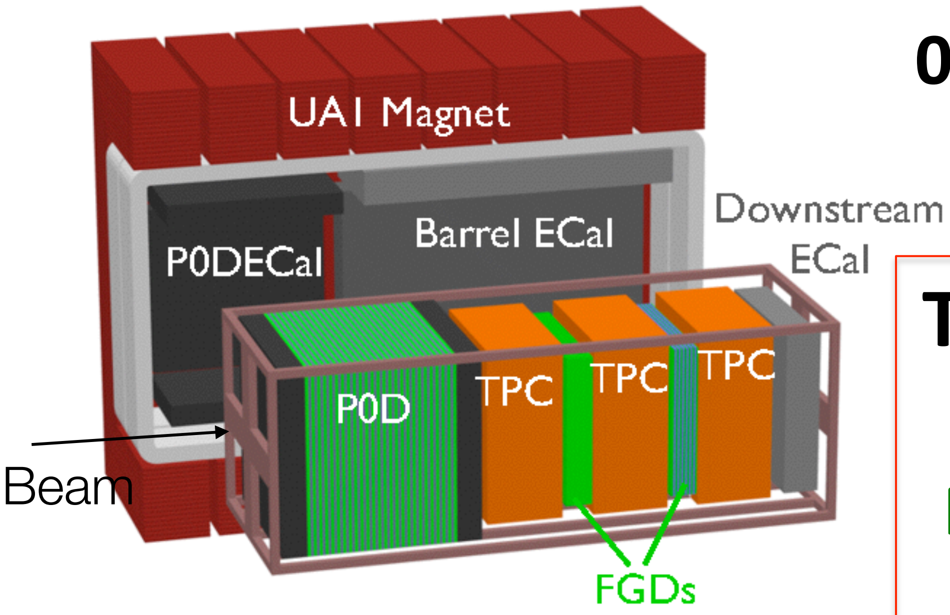
ν:anti-ν mode = 1:3

<u>20% error of intrinsic ν_e can ruin the sensitivity.</u>

<u>< 5% error is ideal.</u>

True osc. param. $sin^2(2\theta_{13}) = 0.084 \pm 0.005, sin^2(\theta_{23}) = 0.5, sin^2(\theta_{12}) = 0.306,$
$\Delta m^2_{21} = 7.5 \cdot 10^{-5} eV^2, \Delta m^2_{32} = 2.4 \cdot 10^{-3} eV^2$

T2K near detectors (ND280)



0.2 T magnetic field

Surrounding ECALs

Tracker: Constrain signal/BG predictions for OA

Fine-Grained Detector (FGD)

active plastic scintillator target*

(+ passive water targets (FGD2))

TPCs

- particle/charge ID
- Momentum measure.

π^0 detector (P0D)

active plastic scintillator targets*

+ passive water targets

+ brass radiator layers

* active targets with segmented X/Y planes

Limitation of current near detectors (1)

- **Detector acceptance**
  - Super-K: 4π coverage.
  - ND280: The large angle reconstruction efficiency is limited to ~10% by geometry of the FGD.
- **Mass fraction of water**
  - Super-K: 100%
  - ND280: 47% (Analyses will use FGD1 and FGD2(water).)
- **Neutrino flux**
  - Super-K: point source
  - ND280: line source

  The diff. is relevant for extrapolating BGs where oscillation effect is small: **$NC\pi^0$** and **intrinsic ν_e**
  - Oscillations change the energy dependence/the flavor of the flux.

Limitation of current near detectors (2)

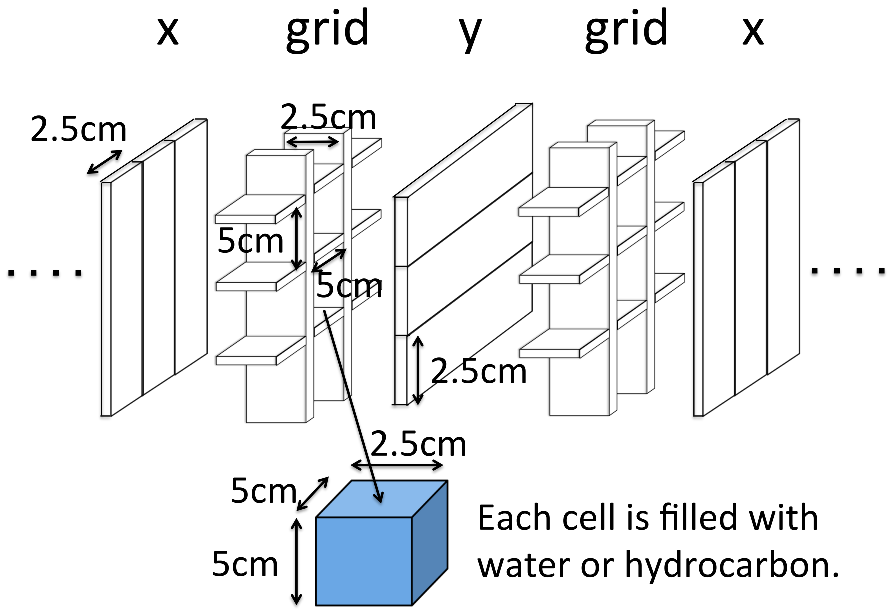
- **Proton reconstruction**
  - Energy/momentum threshold (from track) or energy resolution (from vertex activity) of protons with the current near detector may not be sufficient to give definite answer for CCQE and Multi-nucleon CCQE-like interactions.
- **ν_e measurement**
  - The large amount of material surrounding the inner tracker of the current ND280 is a background source of converting photons ($\gamma \rightarrow e^+e^-$) in FGD for the ν_e measurements.
  - Statistics of ν_e events for $E_\nu < 1.2$ GeV with the current near detectors are too low for a few percent measurement. (~10% stat. error for 3.9e21 POT)

Candidate new ND280 detectors

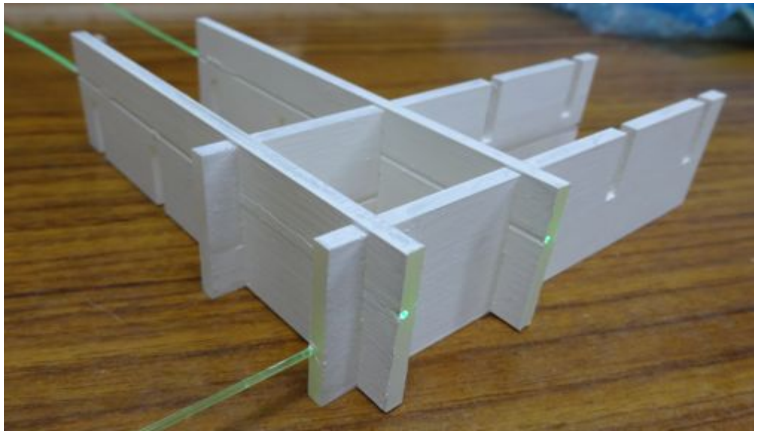
1. 3D grid water detector
2. High pressure TPC
3. Water based scintillator detector
4. Emulsion detector

WAGASCI

- 3D grid-like structure
  - x + grid + y + grid + … layers
  - **4π angular acceptance** for charged particles
  - **H_2O(signal):CH(BG) = 79:21**

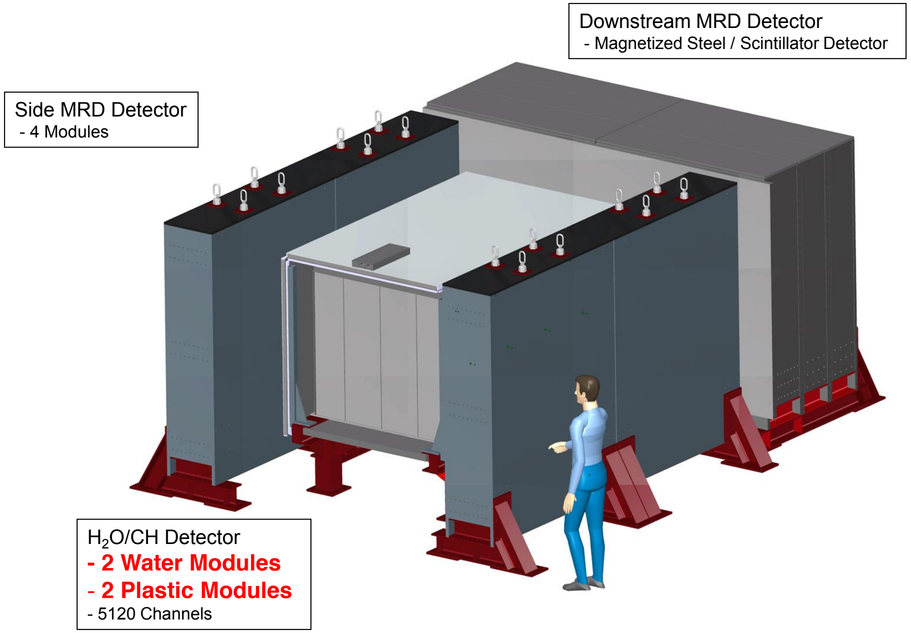


Each cell is filled with water or hydrocarbon.



WAGASCI (J-PARC T59)

An approved test experiment by J-PARC PAC (T59).



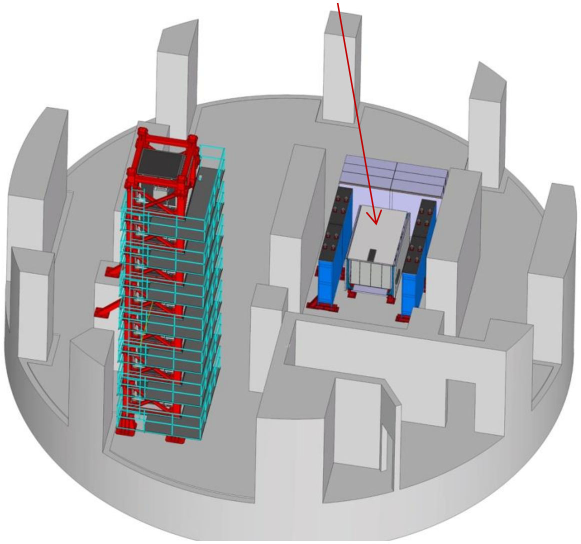
Downstream MRD Detector
- Magnetized Steel / Scintillator Detector

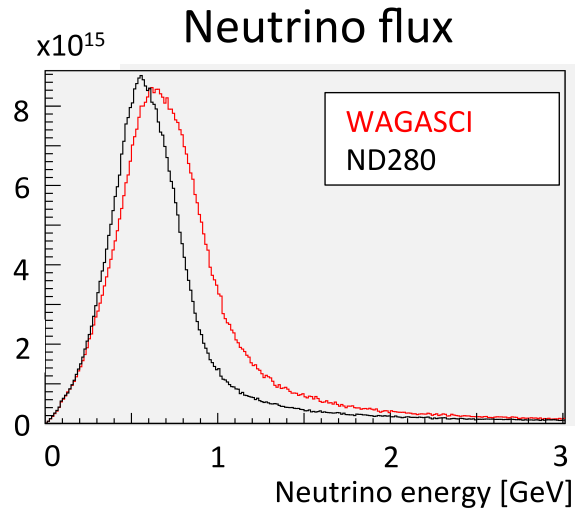
Side MRD Detector
- 4 Modules

H_2O/CH Detector
- **2 Water Modules**
- **2 Plastic Modules**
- 5120 Channels

B2 floor of ND280 pit

(Off-axis angle = 1.6 deg.)





Neutrino flux

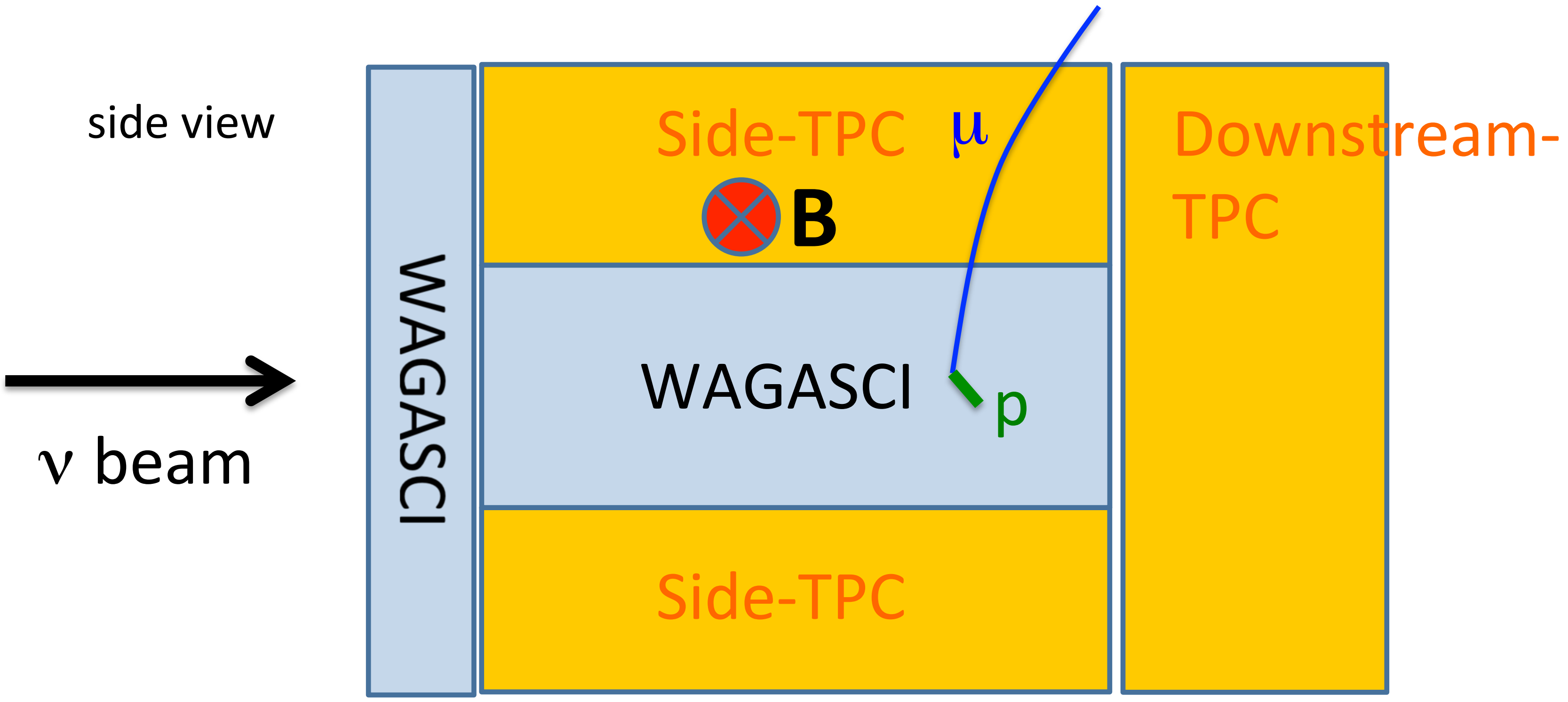
Goals

Measure cross section ratio between H_2O and CH with 4π acceptance/<3% error to increase T2K sensitivity.

Schedule

- 2016: Construction of detectors
- Early 2017: Start beam measurement

WAGASCI in ND280 magnet

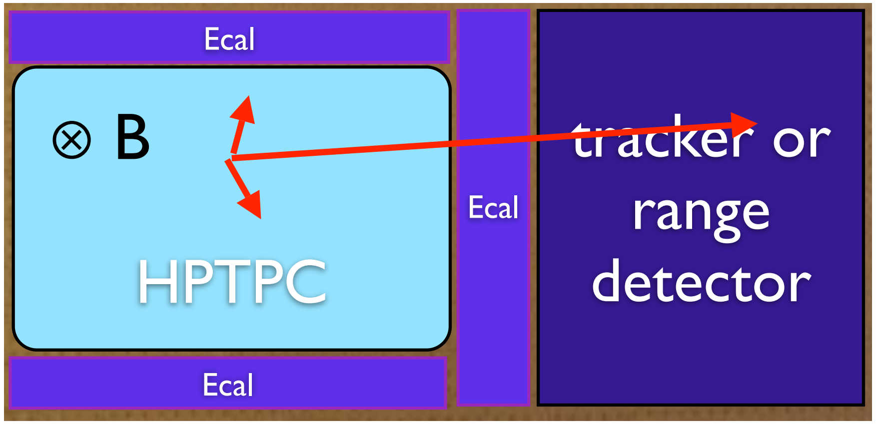


Excellent **charge/particle identification** and **momentum measurement** for large angle tracks with side-TPCs.

High-pressure TPC

- High-pressure TPC
  - Low thresholds.
    ➔ Sensitive to hadronic final state.
  - excellent PID capabilities.
  - Momentum measurement.
  - Almost uniform 4π acceptance.

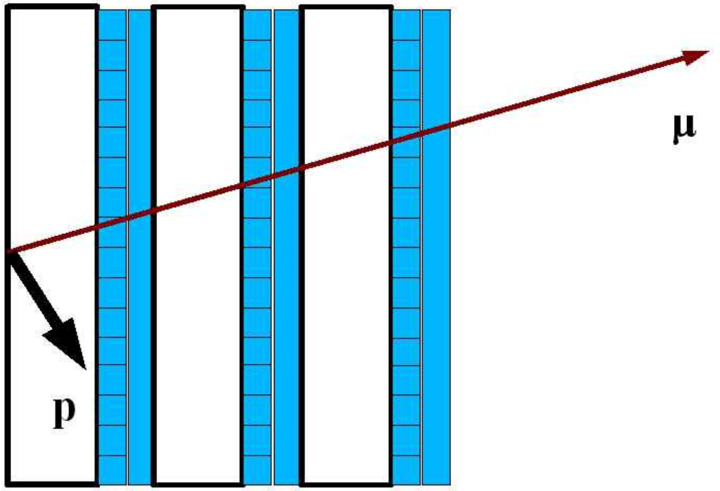
- Goals
  - Multi-nucleon modeling.
  - Multi-pion resonance.
  - Final state interaction.
  - Secondary interaction in detector.



# of CC events assuming full FV.

2x2x2 m^3 20°C	5 bars	10 bars
He	6.65 kg	13.3 kg
	520 evt/10^{21}pot	1040 evt/10^{21}pot
Ne	32.5 kg	67.1 kg
	2543 evt/10^{21}pot	5086 evt/10^{21}pot
Ar	66.5 kg	133 kg
	5203 evt/10^{21}pot	10406 evt/10^{21}pot
CF_4	146.3 kg	293 kg
	11450 evt/10^{21}pot	22893 evt/10^{21}pot

Water based scintillator cells in FGD/P0D

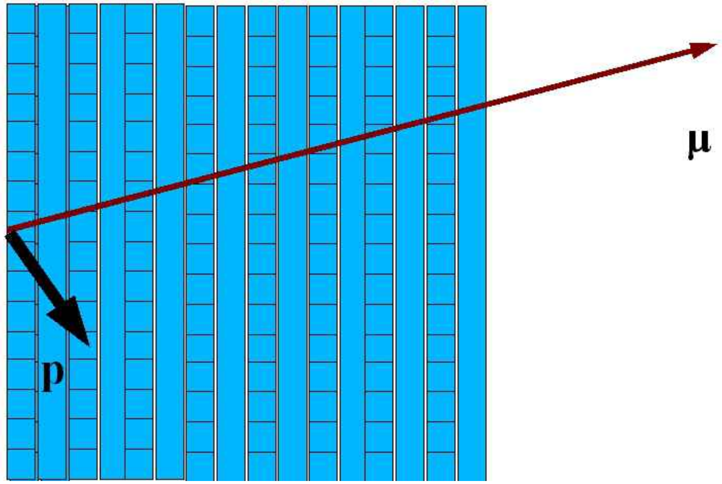


Present near detector:

Passive water layers between plastic scintillator layers

➔Dead region.

➔Low energy recoil protons in passive water produce no signal.



Active scintillating water:

Introduce water based scintillator cells (< 5mm cell size).

➔No dead region.

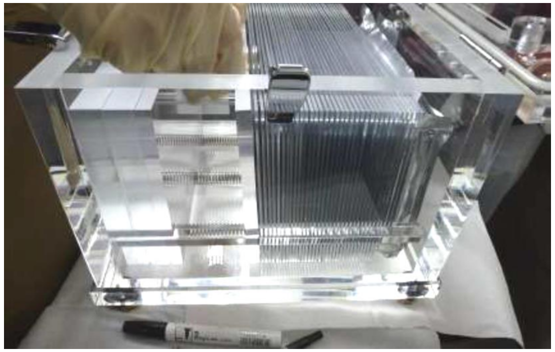
➔All recoil particles detected.

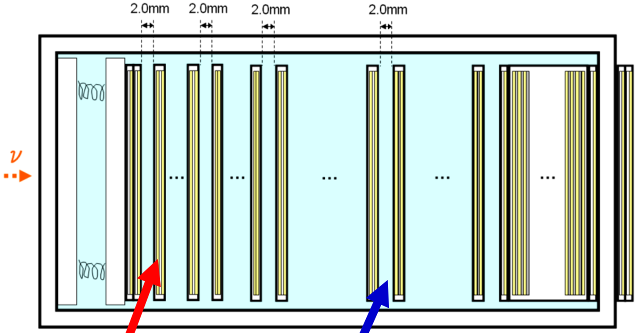
<u>R&D is on-going.</u>

Emulsion detector (J-PARC T60)

An approved test experiment by J-PARC PAC (T60).

Water target emulsion chamber





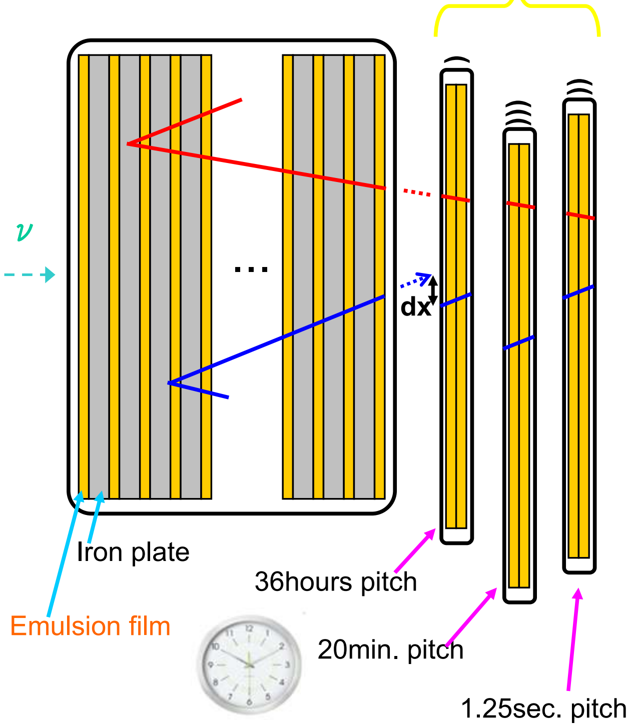
Emulsion films

in Water target chamber

(water layer : 2mm)

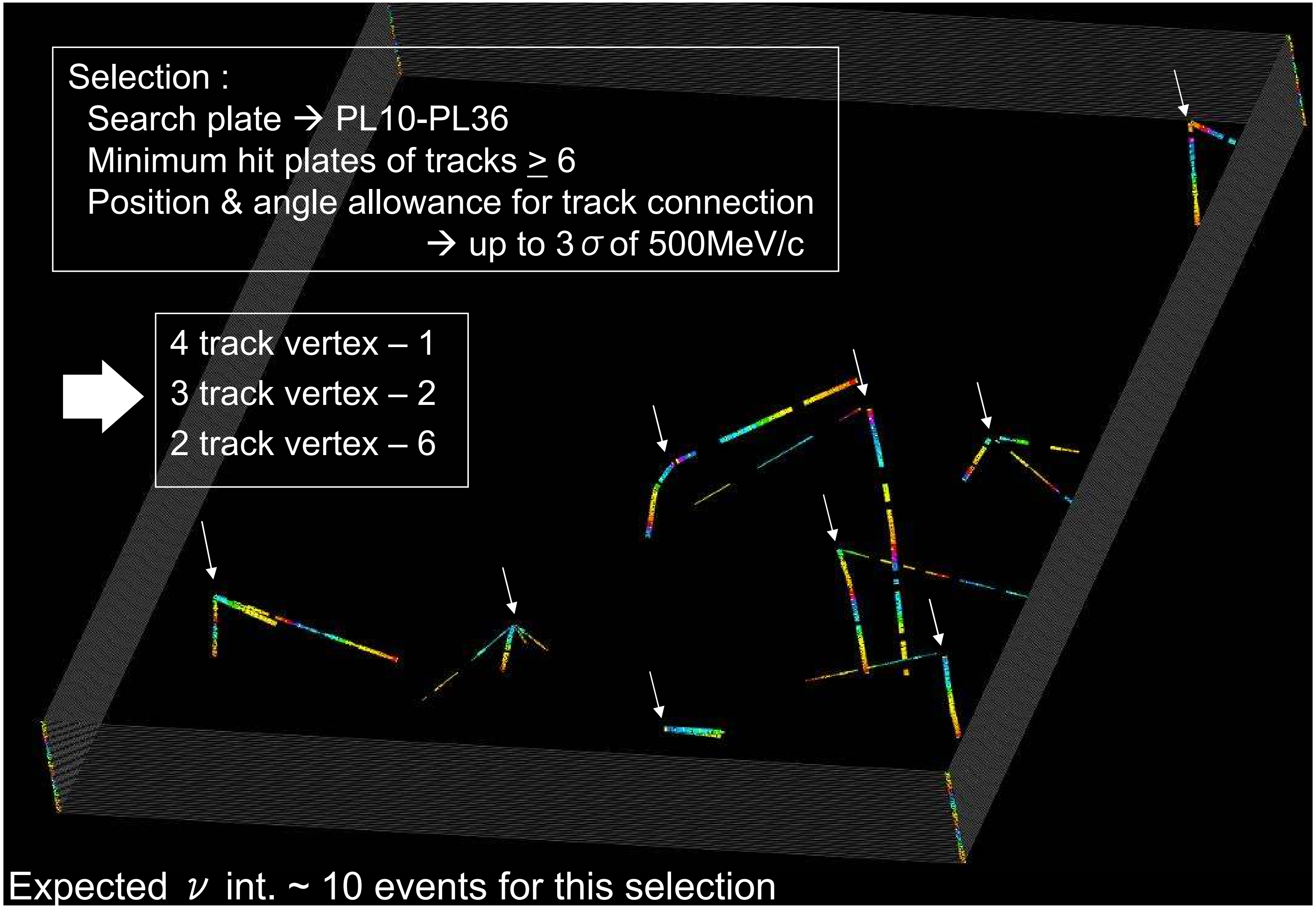
Emulsion shifter

- Time stamps for ν events
- Hybrid analysis with other near detectors



Emulsion detector (J-PARC T60)

Pilot analysis: Multi-track vertex search



Selection :
- Search plate → PL10-PL36
- Minimum hit plates of tracks ≥ 6
- Position & angle allowance for track connection → up to 3σ of 500MeV/c

- 4 track vertex – 1
- 3 track vertex – 2
- 2 track vertex – 6

Expected ν int. ~ 10 events for this selection

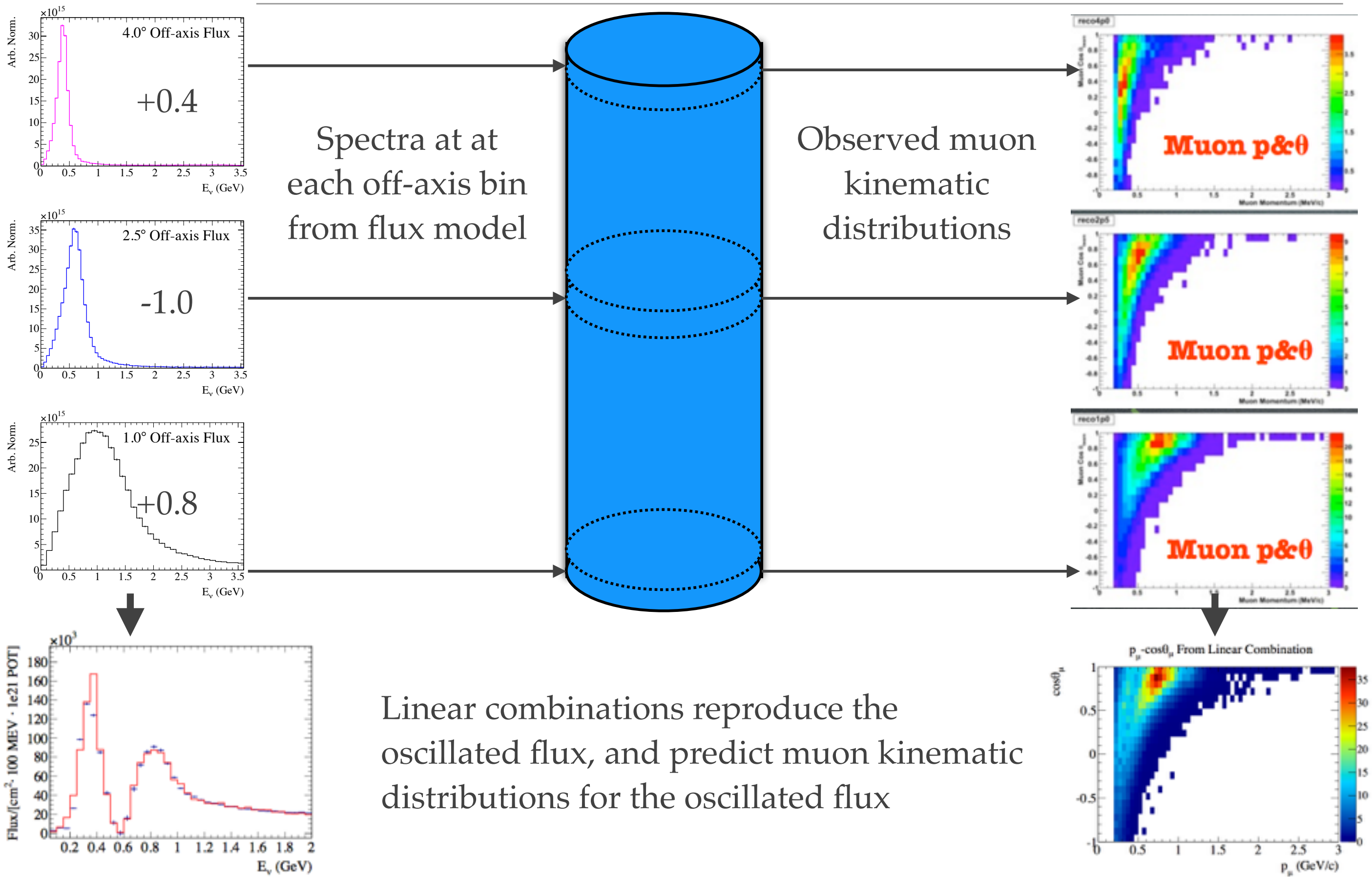
Candidate intermediate detectors (1~2km from target)

1. Water Cherenkov detector with wide off-axis angle coverage
2. Gd-doped water Cherenkov detector

νPRISM

- An experimental method to remove uncertainties of neutrino interaction(+ FSI&SI) from oscillation analysis.

Linear Combinations



Spectra at at each off-axis bin from flux model

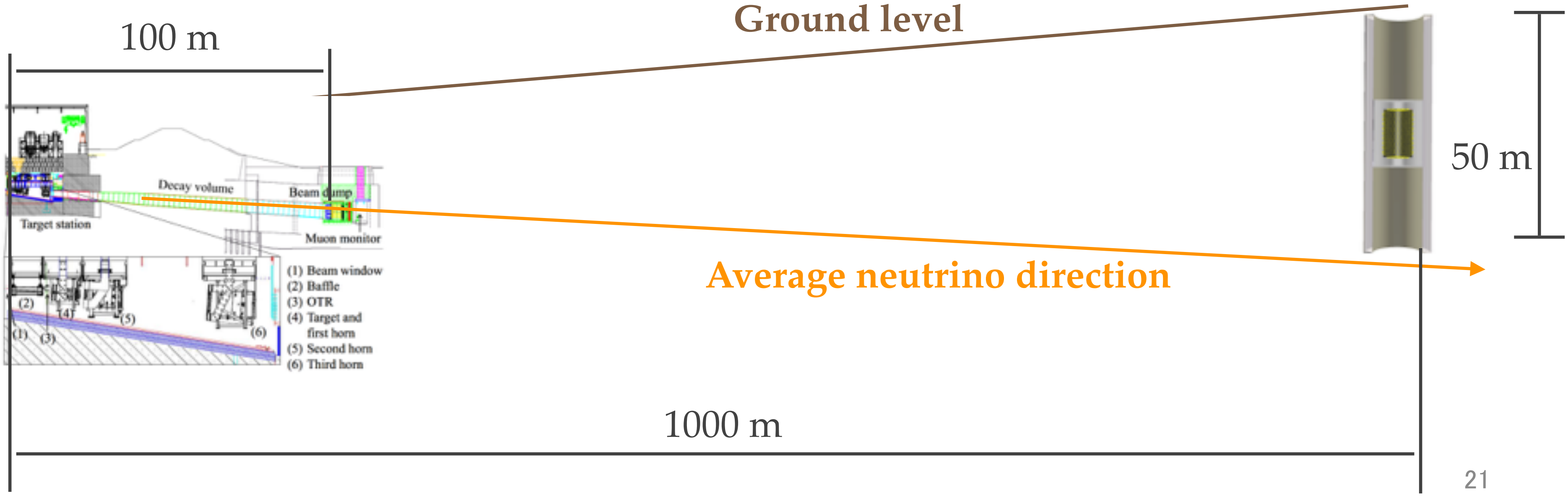
Observed muon kinematic distributions

Linear combinations reproduce the oscillated flux, and predict muon kinematic distributions for the oscillated flux

Use the templates of muon p-θ distribution for the oscillation fit.

νPRISM

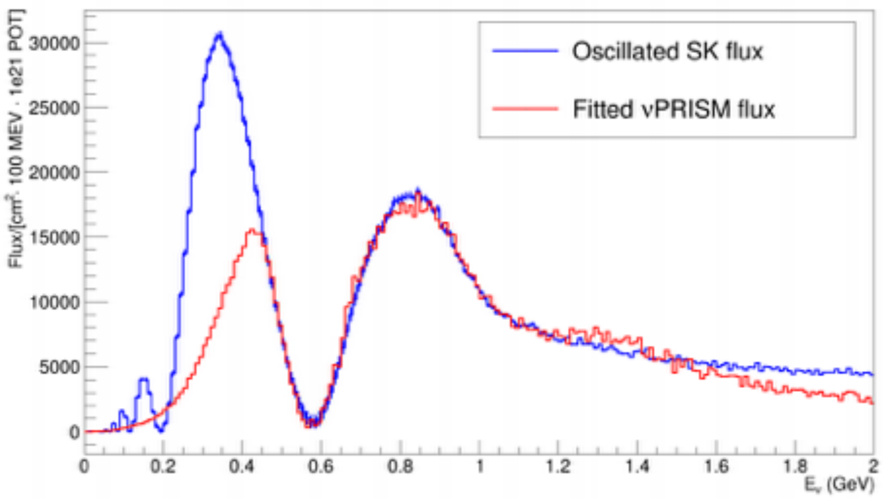
- **Detector**
  - 10m diameter water cherenkov detector (~3000 8 inch PMTs with 40% photo coverage)
  - 50m height detector hall (covers 1-4° off-axis.)
  - Move up and down in the hall to take measurement at different off-axis angles.



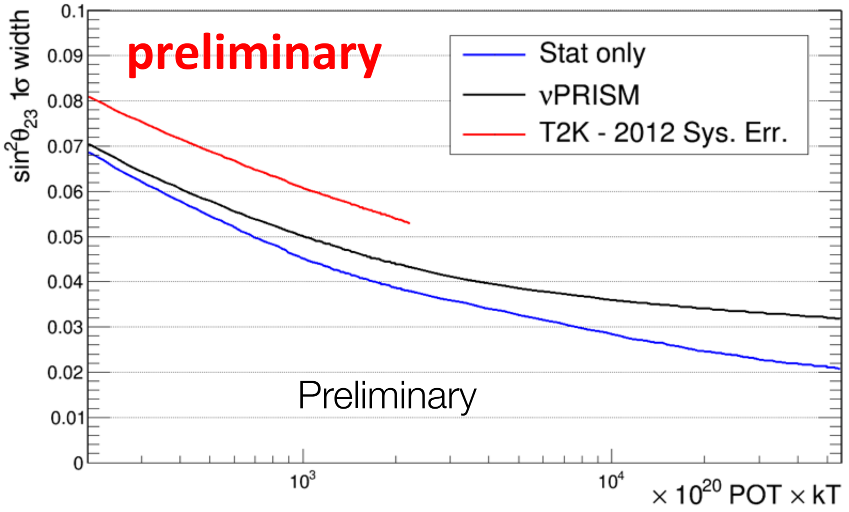
νPRISM

- **ν_μ disappearance analysis**
  - 4.3 % systematic effect on $\sin^2 2\theta_{23}$ from "multi-nucleon" modeling when using ND280. ➔1.2% when using νPRISM.

A template for the oscillated flux.



$\sin^2\theta_{23}$ sensitivity (T2K, ν mode)

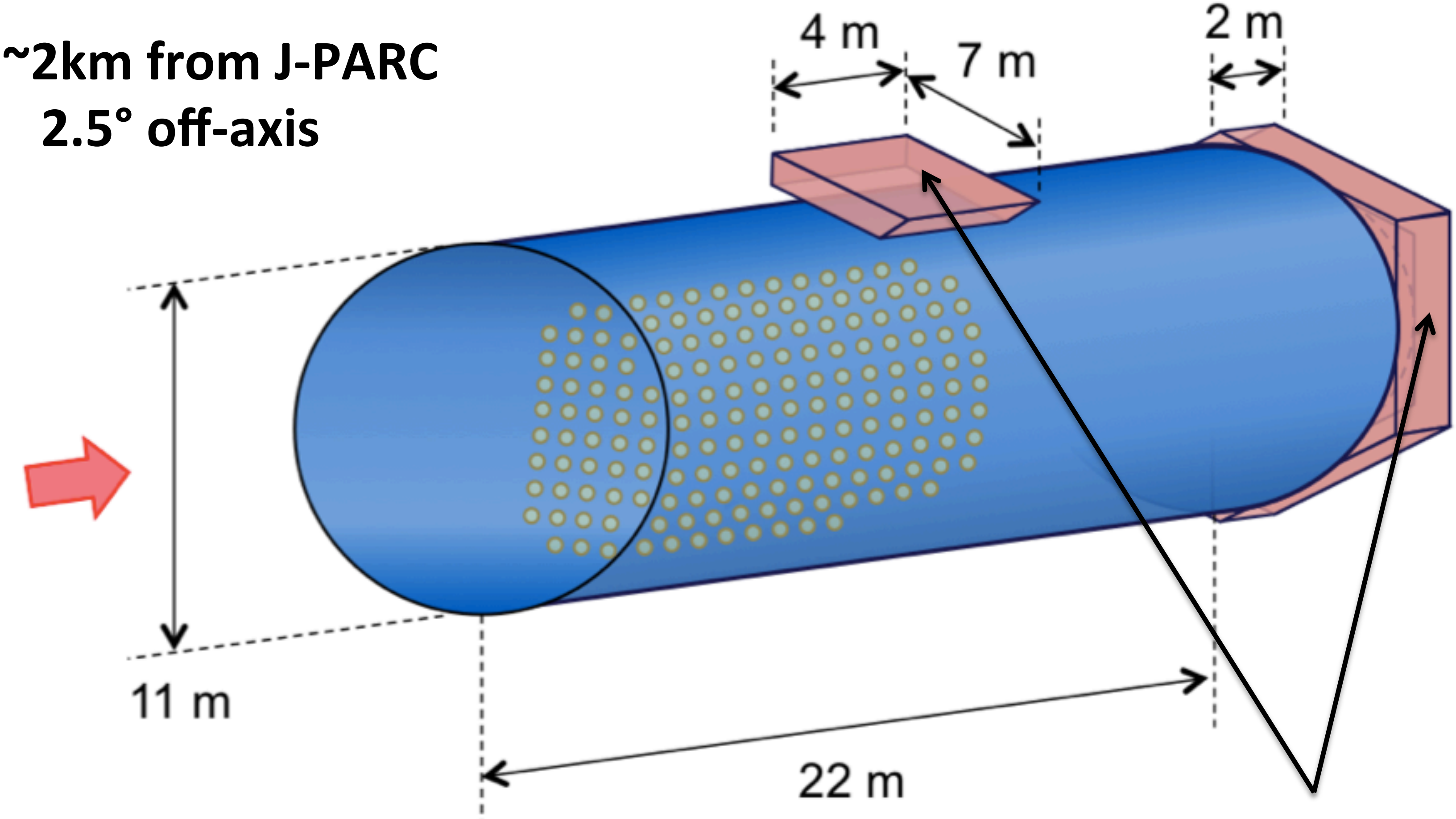


- **Other physics**
  - Short baseline ν_e appearance (Sterile neutrino search).
  - Cross section measurements using monochromatic beams.

TITUS

2kton Gd-doped (0.1%) water Cherenkov detector

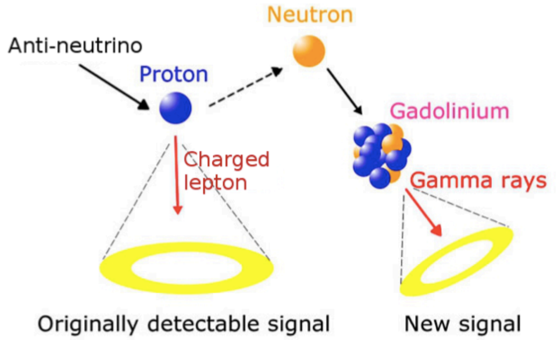
~2km from J-PARC
2.5° off-axis



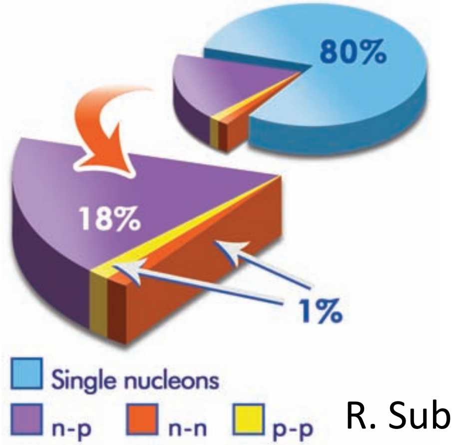
Magnetized muon-range detectors

TITUS

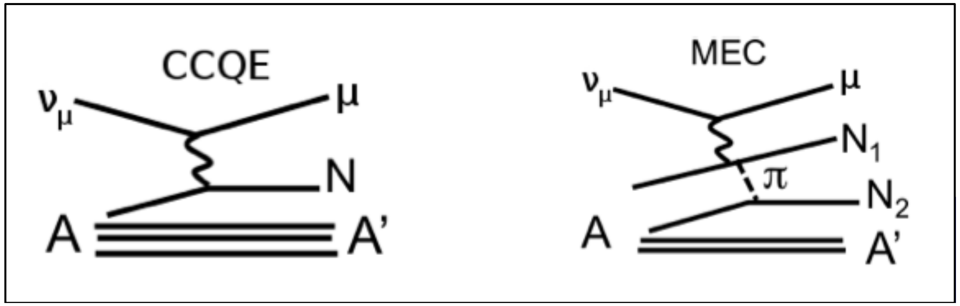
- Neutron capture on Gadolinium:
  - Cross section of 49,000b compared to 0.3b for H
  - 8MeV gamma cascade with 4-5MeV visible energy
  - 0.1% Gd doping: ~90% of neutrons capture on Gd



- New signal to distinguish ν / $\bar{\nu}$ events and different interaction modes:
  - ν_μ CCQE: $\nu_\mu + n \rightarrow \mu^- + p$ 0 neutrons
  - $\bar{\nu}_\mu$ CCQE: $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$ 1 neutron
  - ν_μ MEC: $\nu_\mu + (n + p/n) \rightarrow \mu^- + p + p/n$ 0.2 neutrons on average
  - $\bar{\nu}_\mu$ MEC: $\bar{\nu}_\mu + (p + p/n) \rightarrow \mu^+ + n + p/n$ 1.8 neutrons on average

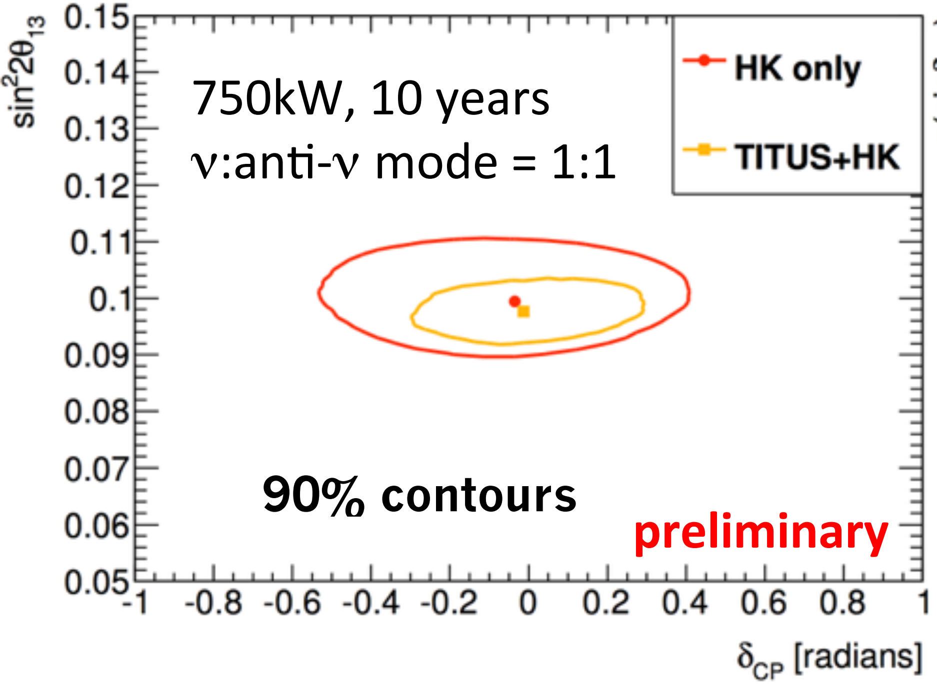


R. Subedi et al., Science **320**, 1476 (2008).



TITUS

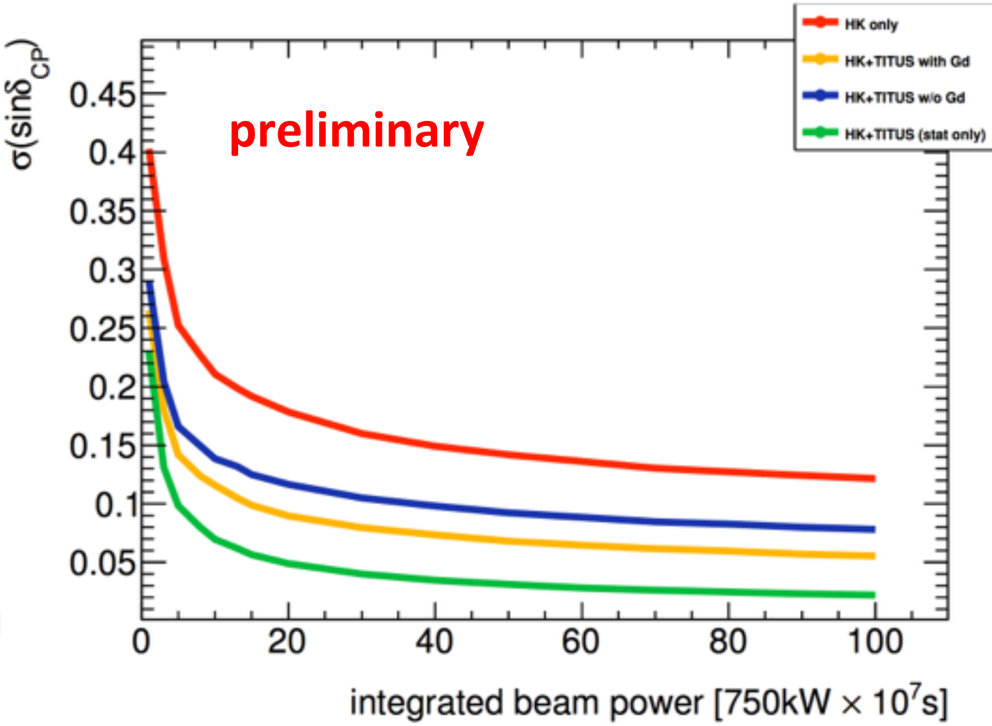
δ_{CP} sensitivity (Hyper-K + J-PARC)



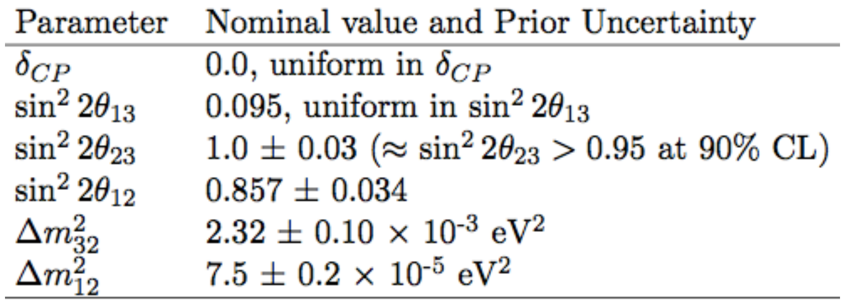
750kW, 10 years
ν:anti-ν mode = 1:1

90% contours

preliminary



preliminary



Parameter	Nominal value and Prior Uncertainty
δ_{CP}	0.0, uniform in δ_{CP}
$\sin^2 2\theta_{13}$	0.095, uniform in $\sin^2 2\theta_{13}$
$\sin^2 2\theta_{23}$	1.0 ± 0.03 ($\approx \sin^2 2\theta_{23} > 0.95$ at 90% CL)
$\sin^2 2\theta_{12}$	0.857 ± 0.034
Δm^2_{32}	$2.32 \pm 0.10 \times 10^{-3}$ eV^2
Δm^2_{12}	$7.5 \pm 0.2 \times 10^{-5}$ eV^2

17% precision improvement
due to neutron tagging

Physics requirements vs. detectors
(my personal view)

	ν_e cross section	H_2O target	4π accep.	Wrong sign BG	NC, Int. ν_e BG	Muon FS vs. ν	Hadronic FS	# of neutron (Gd)	$CC\pi^0$
Current ND280	🟨	🟨	🟨	🟩	🟨	🟨	🟨	🟥	🟨
ND280 (WAGASCI)	🟨	🟩	🟩	🟩	🟨	🟨	🟨	🟥	🟨
ND280 (HP-TPC)	🟥	🟥	🟩	🟩	🟨	🟨	🟩	🟥	🟨
ND280 (WbLS)	🟨	🟩	🟨	🟩	🟨	🟨	🟨	🟥	🟨
ND280 (Emulsion)	🟨	🟩	🟩	🟩	🟨	🟨	🟩	🟥	🟨
νPRISM	🟩	🟩	🟩	🟨	🟩	🟩	🟥	🟨	🟩
TITUS	🟩	🟩	🟩	🟩	🟩	🟨	🟥	🟩	🟩

🟩 = Good 🟨 = OK 🟥 = Not Good

Summary

- Reduction of systematic errors is getting more important in the era of T2K extension* to improve the sensitivity.
  - It becomes more important to constrain the errors with near detector measurements.
- Each new candidate near detector has pros and cons.
  - We should make final decision taking into account complementarity among them.

* Discussion about the extension is just started. Nothing has been decided yet.